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Support for Sustainable Development Policy Decisions

A Case Study from Highway Maintenance

Lucia Elghali[1]*, Sarah J. Cowell[1], Katherine G. Begg[2] and Roland Clift[1]

[1] Centre for Environmental Strategy, School of Engineering (D3), University of Surrey, Guildford, Surrey, GU2 7XH, UK
[2] Institute of Energy and Sustainable Development, De Montfort University, Queen's Building, The Gateway, Leicester, LE1 9BH, UK

* **Corresponding author** (l.elghali@surrey.ac.uk)

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Abstract

Goal, Scope and Methodology. This paper describes a case study carried out as part of a wider programme to provide support for environmental decision-making in the highway maintenance programme of a local government body: Surrey County Council (SCC). UK local authorities are required to demonstrate that sustainable development principles are addressed in service provision, by improving environmental, economic or social well-being and improving public consultation. A methodological approach was developed to meet these requirements by using life cycle assessment (LCA) and multi-criteria decision analysis (MCDA) through the process of decision conferencing.

Results. In projects requiring strategic decisions, difficulties arise in identifying relevant sustainable development criteria and in evaluating maintenance options against these criteria where the context for decision-making is complex and characterised by uncertainty, where multiple public policy objectives compete and a number of decision-makers and key players are affected by the outcome. Clearly, a structured process is needed to engage such stakeholders in the decision process, utilising quantitative and qualitative information. The approach described proved to be capable of fulfilling these requirements.

Conclusions and Recommendations. The approach of combining LCA with MCDA through decision conferencing is capable of further development to support other strategic decision-making activities. However, this illustrative case study has revealed a need for methodological developments in LCA for local, project-level decisions.

Keywords: Decision making; highway maintenance; life cycle assessment; multi-criteria decision analysis; public policy; sustainable development

Introduction

Highway maintenance policies, in the UK and elsewhere, commonly assume that reusing and recycling materials automatically constitutes good environmental performance. For example, the UK Government uncritically promotes reuse of highway materials and incorporation of wastes and by-products into roads (Highways Agency 2003), while the environmental performance of local authority road maintenance projects has often been measured by evaluating the proportion of recycled or secondary materials used.

Materials and techniques have been available for many years to reuse materials or down-cycle them to lower specification uses; the potential environmental and economic benefits of employing these technologies have been widely publicised (see for example Kennedy 1997). However, the basis for assessment has now widened to sustainable development objectives. The Local Government Act 2000 requires local authorities to prepare a 'Community Strategy' to promote or improve the economic, social and environmental well-being of their areas. In principle, highway maintenance is subject to this kind of evaluation. However, no general methodology is yet available for assessing the sustainability of highway maintenance technologies. Approaches based on aggregation or valuation of non-commensurable impacts, such as cost-benefit analysis (CBA), are not appropriate and are frequently counterproductive (Cowell et al. 1997, Elghali 2002a, Elghali 2002b). Therefore, a different approach has been investigated, combining life cycle assessment (LCA) and multi-criteria decision analysis (MCDA) through a process of decision conferencing. The approach has been explored using a specific road maintenance project to reveal its benefits and problems. The Environmental Impact Assessment (EIA) procedure was not considered relevant to this case study, given that the objective was to compare maintenance processes rather than new development projects.

1 Case Study

1.1 Options considered

Six options for the reconstruction of a principal (A class) road were investigated (**Table 1**). They represent three different approaches, each with and without down-cycling of the excavated bituminous waste[1]. The original road consisted of 290 mm of bituminous material over a variable quality sub-base of demolition waste (established by taking core samples). All options were financially viable and technically equivalent. Three sources were used to compile the LCI data required for the six options. Primary data were collected for the in-situ recycling processes. Data sets for the remaining highway maintenance processes were obtained from Stripple (1995, 2001)[2]. Data required to model up-

[1] The engineering project to reconstruct the A232 Cheam Road in East Ewell had been carried out by SCC's Highway Authority.
[2] Although the study was carried out in Sweden, the data were appropriate because the plant used was similar to that used in the UK.

Table 1: Options for road reconstruction

Approach	Option
Conventional reconstruction: all existing bituminous material and sub-base material is removed and replaced with bituminous material to a depth of 290 mm and unbound material to a depth of 150 mm (equivalent to a volume of 290 m^3 and 150 m^3, respectively). Involves excavating 440 m^3 of material.	1: All material excavated from the road is landfilled at a site within a 25 km radius.
	2: All material excavated from the road is used as footway subbase at a site within a 25 km radius.
In-situ recycling using foamed bitumen: bituminous material is removed to a de pth of 40 mm (40 m^3). The existing road material is recycled in-situ to a depth of 200 mm with foamed bitumen (4% plus 2% cement). An overlay of bituminous surfacing is applied (100 mm deep). Involves excavating 40 m^3 of material.	3: All material excavated from the road is landfilled at a site within a 25 km radius.
	4: All material excavated from the road is used as footway subbase at a site within a 25 km radius.
In-situ recycling using cement: bituminous material is removed to a depth of 40 mm (40 m^3). The existing road material is recycled in-situ to a depth of 200 mm with cement (9%). An overlay of bituminous surfacing is applied (100 mm deep). Involves excavating 40 m^3 of material.	5: All material excavated from the road is landfilled at a site within a 25 km radius.
	6: All material excavated from the road is used as footway subbase at a site within a 25 km radius.

Table 2: Impact categories used in the study (derived from Guinée et al. 2002, p. 146)

Impact Category	Characterisation Factors Used
Abiotic Resource Depletion (Energy)	Total Non-Renewable Energy Used
Climate Change	Houghton et al. (1996)
Human Toxicity[a]	Guinée et al. (1996), Huijbregts et al. (2000)
Freshwater Aquatic Ecotoxicity[a]	Guinée et al. (1996), Huijbregts et al. (2000)
Terrestrial Ecotoxicity[a]	Guinée et al. (1996), Huijbregts et al. (2000)
Photochemical Oxidant Formation	Heijungs et al. (1992), Finnveden et al. (1992) (in Lindfors et al. (1995))
Acidification	Heijungs et al. (1992), Lindfors et al. (1995)
Eutrophication	Heijungs et al. (1992)

[a] The toxicity assessments were carried out initially using characterisation factors from Guinée et al. (1996). Further analysis was carried out using a second method as a sensitivity analysis later (Huijbregts et al. 2000), which gave a different ranking of the options. The former were used to provide data for the MCDA model described in Section 2.3.3, as they were available at the time the decision conference had been scheduled.

stream and downstream processes were available in the TEAM™ software.

Given that a multi-criteria approach was adopted, it was essential to use an approach to impact assessment (LCIA) which shows impact categories separately and transparently, so that the results could be conveyed to stakeholders, including officers of Surrey County Council, who had no prior exposure to LCA. Approaches which aggregate impacts, such as the Ecopoints (Ahbe et al. 1990), EPS (Steen and Ryding 1992) or Eco-Indicator 99 (Goedkoop and Spriensma 2001) methods, were therefore rejected in favour of the problem-oriented approach. The specific approach used was that recommended by Guinée et al. (2002, p. 537). The impact categories included and assessment methods used are summarised in **Table 2.**

1.2 The LCA results

Table 3 shows the life cycle impacts for the six options, expressed relative to Option 1 in **Fig. 1**[3]. One alternative – Option 6 – shows the lowest impacts across most impact categories[4]. However, all the recycling options show generally lower impacts than Option 1 (landfilling waste), and the comparison between them is sensitive to local details such as road transport distances. Thus, the LCA results support the common assumption that re-using materials is to be encouraged, but confirm that the ranking of alternative recycling technologies may differ between specific cases. Site-specific considerations and localised impacts enter into the comparison, and proved to be critical in this particular case. They include:

- The transportation requirements for materials and waste;
- The expected life of the road;
- Proximity to receptors sensitive to specific toxic emissions;
- The hydrogeological properties of the surrounding substrata, which affect the leaching of materials from the road;
- Any requirement to add or remove material to raise or lower the road profile, either to tie into surrounding infrastructure or for strengthening;
- The need to account for successive multifunctional uses (i.e. systematic down-cycling) of bituminous materials;
- The engineering requirements for the relative thickness of each road layer.

1.3 Using the LCIA Results with an MCDA Framework through the Process of Decision Conferencing

1.3.1 The Development of MCDA Methodology

Keeney and Raiffa (1993) first developed decision theory for MCDA[5] in 1976, based on the work of von Neumann and Morgenstern (1953) who developed a normative[6] deci-

[3] For full details of the LCA results and methodology, see Chapter 6, Elghali (2002a).

[4] There were some exceptions. For acidification, Options 2 and 4 performed marginally better; landfilling of waste was the major contributor in this category. For eutrophication, Option 4 performed marginally better; high scores for this category were associated with high road transport and large volumes of landfilled waste (most notably in Option 1). Air emissions from cement production accounted for the increased scores for Option 6. The toxicity results were treated with caution, since the ranking of options changed using the two alternative sets of characterisation factors (see Fig. 1 and Table 3).

[5] The term multi-criteria decision analysis (MCDA) is used synonymously here with multi-attribute decision analysis (MADA), following DETR, 2000 (p. 46). This is common practice, due to the close correspondence of attributes and criteria. A criterion here is defined as "one of a number of measures against which options are assessed and compared in a multi-criteria analysis for the degree to which they achieve objectives" (p. 144).

[6] This refers to theoretical approaches to determine how rational individuals should make choices between options.

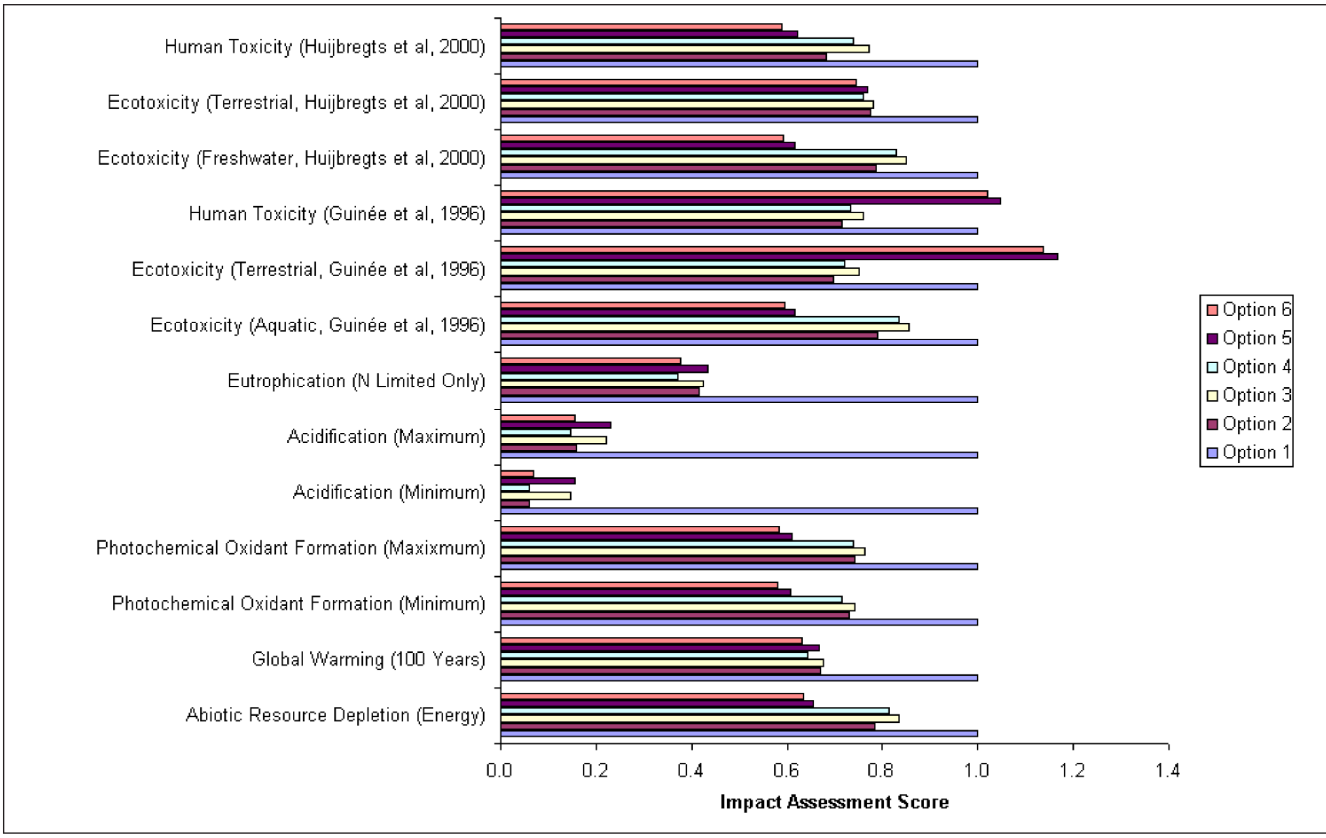

Fig. 1: LCA results for all options plotted relative to the results for Option 1

Table 3: Summary of LCA results

Impact Category (units)	**Options**					
	1	**2**	**3**	**4**	**5**	**6**
Non-renewable energy used (MJ x 10^6)	3.88	3.04	3.24	3.15	2.54	2.45
Global Warming, 100 years (kg carbon dioxide equivalents x 10^5)	2.19	1.46	1.48	1.41	1.46	1.38
POCP Minimum (kg ethene equivalents x 10^2)	1.62	1.19	1.21	1.16	0.99	0.94
POCP Maximum (kg ethene equivalents x 10^2)	7.01	5.20	5.35	5.17	4.27	4.09
Acidification Minimum (kg sulphur dioxide equivalents x 10^3)	4.36	0.26	0.64	0.27	0.67	0.30
Acidification Maximum (kg sulphur dioxide equivalents x 10^3)	6.05	0.95	1.35	0.88	1.40	0.93
Eutrophication, N Limited Only (kg phosphate equivalents x 10^2)	2.99	1.25	1.27	1.19	1.30	1.13
Aquatic Ecotoxicity[a] (kg 1,4-dichlorobenzene equivalents x 10^2)	6.28	4.96	5.36	5.23	3.86	3.73
Terrestrial Ecotoxicity[a] (kg 1,4-dichlorobenzene equivalents x 10^4)	3.02	2.11	2.26	2.18	3.52	3.43
Human Toxicity[a] (kg 1,4-dichlorobenzene equivalents x 10^3)	2.00	1.43	1.52	1.46	2.10	2.04
Freshwater Aquatic Ecotoxicity[b] (kg 1,4-dichlorobenzene equivalents x 10^3)	2.91	2.29	2.48	2.41	1.80	1.73
Terrestrial Ecotoxicity[b] (kg 1,4-dichlorobenzene equivalents)	3.03	2.35	2.37	2.31	2.33	2.26
Human Toxicity[b] (kg 1,4-dichlorobenzene equivalents x 10^4)	4.02	2.74	3.10	2.97	2.50	2.39

[a] Using characterisation factors from Guinée et al. 1996
[b] Using characterisation factors from Huijbregts et al. 2000

sion theory to demonstrate how individuals should rationally choose between a number of options. The theory explained mathematically how to derive the subjective expected utility (SEU) values for options considered in decisions, where a 'rational individual' acting as a single decision maker would choose the option having the maximum SEU value[7]. Within this general framework, Keeney and Raiffa developed procedures for calculating 'multi-attribute utilities' for circumstances closer to real decision making, which included group decisions involving multiple objectives, uncertainties and risk. Keeney and Raiffa demonstrated that a simple linear addi-

[7] Pages 15–31 of von Neumann and Morgenstern (1953) introduce the concept of utility.

tive model can often be used as an approximation to von Neumann and Morgenstern's SEU model, having the form:

$$S_i = w_1 s_{i1} + w_2 s_{i2} + \ldots + w_n s_{in} = \sum_{j=1}^{n} w_j s_{ij} \qquad (1)$$

where

S_i is the total score for each option
i is the option requiring evaluation
j is the criterion scored
s_{ij} is the preference score for each criterion
w_j is the weight for each criterion
n is the number of criteria

This simplification had the effect of operationalising the SEU model, since von Neumann and Morgenstern had not demonstrated how individual utilities describing consequences could be evaluated (DETR 2000, p. 116). Keeney and Raiffa also extended the general single attribute utility case to situations where the consequences are uncertain and/or cannot be described in terms of a single attribute such as monetised cost and benefit (1993, p. 27).

Keeney and Raiffa suggested a number of ways to use MCDA models to facilitate group decision-making, including the crucial role of sensitivity analyses. In particular, they note that sensitivity analysis is useful where agreement on valuation for certain criteria cannot be reached, as it allows the group to see how their range of values affects the outcome. This is useful in that the model can be explored even without a consensus decision. Thus, it provides a sound basis for arbitration and enables compromise through discussion of the underlying assumptions and values at each stage of development of the model (1993, p. 541). This feature of MCDA is exploited in Phillips' Decision Conferencing methodology, described in Section 1.3.2.

1.3.2 MCDA using decision conferencing

In the case study, the methodology adopted was that recommended in the UK Government Guidance on Multi Criteria Analysis[8]. The steps in MCDA are summarised in **Table 4**.

Table 4: Detailed steps in undertaking MCDA (DETR 2000, p. 50)

1.	**Establish the decision context.**
1.1	Establish aims of the MCDA, and identify decision makers and other key players.
1.2	Design the socio-technical system for conducting the MCDA.
1.3	Consider the context of the appraisal.
2.	**Identify the options to be appraised.**
3.	**Identify objectives and criteria.**
3.1	Identify criteria for assessing the consequences of each option.
3.2	Organise the criteria by clustering them under high-level and lower-level objectives in a hierarchy.
4.	**'Scoring': assess the expected performance of each option against the criteria. Then assess the value associated with the consequences of each option for each criterion.**
4.1	Describe the consequences of the options.
4.2	Score the options on the criteria.
4.3	Check the consistency of the scores on each criterion.
5.	**'Weighting': assign weights for each of the criterion to reflect their relative importance to the decision.**
6.	**Combine the weights and scores for each option to derive an overall value.**
6.1	Calculate overall weighted scores at each level in the hierarchy.
6.2	Calculate overall weighted scores.
7.	**Examine the results.**
8.	**Sensitivity analysis.**
8.1	Conduct a sensitivity analysis: do other preferences or weights affect the overall ordering of the options?
8.2	Look at the advantages and disadvantages of selected options, and compare pairs of options.
8.3	Create possible new options that might be better than those originally considered.
8.4	Repeat the above steps until a 'requisite' model is obtained.

Decision conferencing represents one possible approach to 'designing the socio-technical system' for conducting the MCDA (step 1.2 of Table 4) and is comprised of "an intensive, two-day problem-solving session attended by a group of people concerned about a complex issue with which an organisation is faced" (Phillips 1989). This involves the immediate creation of a computer model, incorporating the different viewpoints of the participants. During the process of refining the model and testing the sensitivity of its assumptions, the process engenders a common understanding of the dimensions of the problem and, ideally, agreement on the way forward. Therefore, the process of carrying out the analysis is at least as important as the results obtained, and may be more important. Decision conferences have found practical applications in many contexts, ranging from resolving siting problems for nuclear waste facilities to formulating corporate strategies[9].

Although Phillips notes that "every decision conference is different" (1989, p. 96), a number of stages are commonly practised or observed. An experienced facilitator assists a group of decision makers and key players to structure their thinking about the decision. The facilitator's role is to encourage creative thinking to identify key issues, problem modelling and interpretation of results, while the analyst

[8] A manual published by the UK Government gives advice on using multi-criteria analysis techniques in public policy decisions (DETR 2000). It is intended to complement economic appraisal methods already in use and to utilise the types of data already collected, which is implied by its numerous references to the use of CBA techniques (for example, see page 9). However, from Chapter 6 onwards, the manual acknowledges that extensive application of CBA to transport policy formulation and implementation has revealed the limitations of the approach and has raised the need to find "more comprehensive appraisal procedures" (2000, p. 74). MCDA is one of a number of techniques discussed which can contribute to a more robust basis for public policy decisions. In particular, the authors state that the "key motivation for using MCDA [...] is the need to accommodate formal analysis criteria that are not easily expressed in monetary terms, or which would be misleading to decision makers if monetised" (2000, p. 75). In this sense, the manual encourages the wider use of MCDA as an alternative to economic appraisal, in 'an attempt to improve the clarity of the decision-making process' (2000, p. 75). The manual has been adopted as the official guidance of the Office of the Deputy Prime Minister (ODPM) and has been published online at <http://www.odpm.gov.uk/stellent/groups/odpm_about/documents/page/odpm_about_608524.hcsp> (last accessed 01/04/05).

[9] A number of examples are given in Chapter 7 of the UK Government Guidance on Multi Criteria Analysis (DETR 2000). A more recent example is the application of MCDA for the UK Government's Air Quality Strategy (see <http://www.defra.gov.uk/environment/airquality/mcda> for details of this project, last accessed 05/04/05).

builds the computer model and assists the facilitator (1989, p. 95). Firstly, the facilitator elicits information from the group to assist them in defining the important aspects of the problem situation, which includes defining decision options and criteria (Steps 1 to 3 in Table 4). The criteria used to distinguish preferences between options are normally elicited directly from the group, ensuring that:

- A distinction is made between higher and lower level objectives, where fundamental criteria form the lowest level in the value tree[10]. A fundamental criterion has been reached when it cannot be broken down further into constituents;
- All the criteria are mutually preference independent (i.e. the preference scores for all criteria should be independent). This is essential if a simple linear additive MCDA model, in the form of Eq. (1), is to be used for calculating the weighted scores.

Once the nature and context of the problem have been formulated, a structural representation of the problem is created as a 'value tree', showing a hierarchy of the aggregation of objectives. The facilitator then uses the group to provide content to score and weight the criteria, enabling a model describing the group's thinking about the problem to be constructed (Steps 4 and 5 in Table 4). Finally, the MCDA model generated can be projected for inspection by the group (Steps 6 and 7 in Table 4). The initial results can also be tested for sensitivity by changing assumptions and hence data inputs in the model (Step 8). In the final stages and after much iteration, the group can use the experience gained in the modelling process to summarise key issues and conclusions. A list of actions is compiled as the last stage of the process. This enables the participants to begin implementing the preferred alternative(s) immediately when they return to normal duties.

1.3.3 Adapting this approach for the case study

A number of authors have postulated that multi criteria analysis methods may provide a means to structure LCIA to improve decision support[11] (for example, see Seppälä et al. 2002). However, this case study did not follow this view of the relationship between these methodological approaches. The decision in this case study involved evaluating the options against diverse sustainable development decision criteria, many of which lie outside the scope of a conventional LCA study. It was therefore logical to use the LCIA results for the six options within a MCDA framework through the process of decision conferencing, to give a more complete assessment of the options against a wider range of SCC policy objectives[12]. It was also envisaged that using the decision conferencing approach would address the need to support group decision-making (see Section 1.3.2). The aims were to:

- Establish the decision context and explore the issues;
- Create a model in the form of Eq. (1) to aid thinking using HIVIEW™ software[13];
- Explore the model created using sensitivity analyses to validate findings and ensure robustness;
- Develop shared understanding of the problem and commitment to implementing the findings.

The participants were selected to represent the values of different policy groups drawn from across Surrey County Council. In this case, a single person acting as both decision analyst and facilitator elicited information from the group to assist them in defining the important aspects of the problem (Steps 1 to 3 in Table 4). After the first attempt to elicit criteria from the group, the LCA results were presented by an LCA analyst. This information was used later in the process to provide data to evaluate environmental criteria, but the impact category scores were not simply used directly. It was not assumed from the start that all of the information from the LCA would be useful to the process, as environmental criteria were subjected to the same process as all others educed from the participants; LCA information was only included in the model where participants identified it as important. To qualify for inclusion, criteria needed to have direct relevance to the decision at hand and to differ significantly between the six options evaluated.

The elicitation process was conducted from a 'bottom-up' perspective: the fundamental criteria were derived first, and then grouped under higher level objectives as necessary to enable analysis of aggregated results. Once the nature of the problem had been formulated, a structural representation of the problem was created as a value tree. Scoring and weighting of the criteria was then conducted (Steps 4 and 5 in Table 4). In this case, these stages were carried out as a separate exercise. To score each option to reflect the magnitude of the consequences, it was necessary to structure a separate consequence table similar to the value tree for each, including every criterion involved in the decision and based on two assumptions about the criteria. Firstly, the method for combining assessments on separate criteria into an overall assessment of weighting was compensatory, so that lower scores for an option on some criteria could be offset by greater scores on other criteria; i.e. trade-offs were modelled to give a weighted average score as an output from the model. Secondly, it was assumed that the preferences were mutually independent; i.e. the scores given to an option against one decision criterion were not affected by the scores given against any other criterion. This was checked rigorously to avoid double counting (see Section 1.3.2).

For each of the criteria, the scores were reduced to dimensionless scales which indicated the relative preference for the consequences associated with the options. The top of the preference scale was assigned a preference value of 100

[10] The use of the descriptors 'higher level' and 'lower level' in this context refers to the position of objectives in a value tree and not to their relative importance.

[11] The use of multi-criteria analysis methods has been proposed as a means to address some of the difficulties encountered with valuation in LCA studies (Miettinen and Hämäläinen, 1997). For example, Seppälä (1998) has used this approach to create a decision analysis impact assessment (DAIA) using the general framework proposed by multi-attribute value theory.

[12] A full audit trail describing the development of the value tree with the decision makers and key players is provided in Chapter 7, Elghali (2002A).

[13] This software is routinely used by decision conferencing facilitators to construct the MCDA model as described in Section 2.3.1 and 2.3.2. It has been developed by Catalyze Ltd. (with Professor L Phillips) specifically for this purpose and is commercially available. Further information can be found on their website at <http://www.catalyze.co.uk/search.html?/hiview_body.htm> (last accessed 23 September 2005)

and referred to the consequences associated with the most preferred option; similarly the least preferred option was assigned a preference value of 0. The remaining options were then scored relative to these two options so that the differences in the numbers reflected the strength of preferences for the consequences. This allowed the use of quantitative and qualitative information: quantitative data scores were simply transformed linearly into an equivalent preference score on a 0–100 scale, while qualitative scores were elicited directly. Following scoring, the method of 'swing weighting' was used to elicit weights for the criteria. In a similar manner to the scoring process, this is based on comparing differences, in this case the significance of the range from 0 to 100 in one criterion compared to the range for another criterion. In other words, "the weight on a criterion reflects both the range of difference of the options, and how much that difference matters" (DETR 2000, p. 62).

The HIVIEW ™ software was used to calculate weighted scores at each level in the value tree for each option and these were summed to give the overall preference score for each option[14]. The results were displayed to the group to show the outcome. The initial results were tested for sensitivity by changing assumptions and, hence, data inputs in the model. Although the steps in Table 4 appear to be discrete procedures, they are highly iterative in practice. This allowed continual and reflexive refinements to the model as it was developed.

1.4 Key results from the decision conference

The value tree obtained is shown in **Table 5**, demonstrating how the elicited criteria (with their definitions) were organised by grouping them under intermediate objectives until the top level objective was reached. The top level objective was 'maintenance', which is achieved by the trade-offs shown further down the value tree and represents the overall result of the analysis. The next level down shows 'costs' and 'benefits' as objectives. The group was interested in this top level trade-off, as it reflected most closely the demands placed on local authorities to demonstrate 'Best Value' in service provision.

The 'costs' objective was concerned with minimising costs incurred in the reconstruction of the road. Criteria contributing towards this objective included direct and indirect financial costs to the local authority. The 'benefits' objective was concerned with maximising the benefits associated with reconstruction and included social and environmental criteria. Where any criterion was actually describing an adverse effect, an inverse scoring scale was used to express the group's preference. For example, the social 'disruption' criterion was scored so that options causing the least disruption scored 100 on the preference scale, whilst those causing the most scored 0. Similarly, options with high preference scores against environmental criteria (e.g. dust) or financial criteria (e.g. process cost) were associated with low potential environmental impacts or costs. **Table 6** provides a summary of the scores and weights obtained from the model. It is interesting to note that the three highest weighted criteria in the study were 'Process', 'Disruption' and 'Local acceptability'. None of these criteria were derived from LCA data; they relate to different socio-economic criteria used to evaluate options in the decision process.

Fig. 2 is an important plot showing the trade offs involved at the top level of the value tree between aggregated preferences for each option against the cost's and benefit's objectives. The key differences compared to the assessment based on the LCIA alone were as follows. Firstly, the ranking was slightly different: Option 4 was the most preferred (rather than Option 6 as in the LCA study), since it scored most highly on both cost and benefit objectives. The score for Option 4 was close to 100 on both preference scales, with 6 and 3 only slightly less preferred. Option 5 was also preferred substantially over Options 1 and 2, and would still represent a good alternative if the other three options were not available for any reason. Option 1 was least preferred by a high margin, demonstrating that it was preferable to use any of the recycling options in the case study. It is also interesting to note that, in contrast with the LCIA results, Option 2 could only compete with the in-situ recycling options (3, 4, 5 and 6) if performance on the costs and local environment criteria were improved dramatically. This reveals a clear preference between the different recycling options, depending on evaluations of their performance against a range of sustainable development criteria.

Testing the sensitivity of the model to differences of opinion about weights and scores showed the outcome to be robust. **Fig. 3** shows the results of one of the many sensitivity analyses carried out during the decision conference. The weights

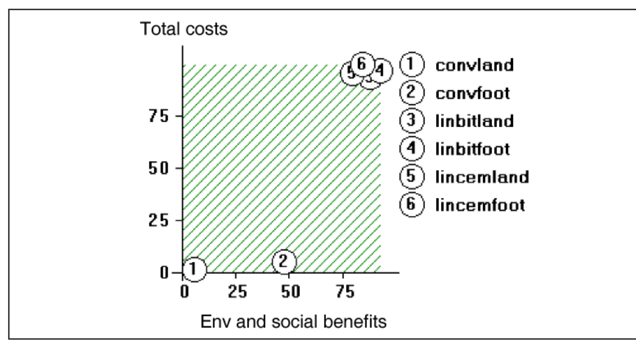

Fig. 2: Weighted preference scores for 'costs' and 'benefits' objectives

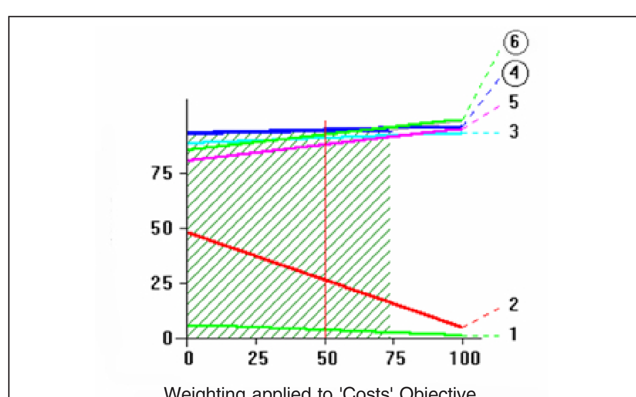

Fig. 3: Variance of preference scores obtained for each option with weighting applied to 'costs' objective

[14] The theoretical basis for this procedure has been discussed in Section 1.3.1.

Table 5: Value tree created for the case study

Name of Criterion	Intermediate Objectives	Higher Level Objectives	Highest Level Objective
Process The actual 'bid price' for the method of reconstruction, fixed by contract in £/m^2.	(None)	*Costs* This objective is concerned with minimising costs incurred in the reconstruction of the road.	*Maintenance* This is the overall objective of achieving reconstruction of the road while maximising contribution towards sustainable development objectives.
Failure Additional risk from using materials or processes which either were more difficult to use or with unknown performance characteristics when used on the road.			
Public Relations The administrative costs to SCC caused by dealing with aspects of disruption.			
Local Acceptability The anticipated public perception of the proposed works, assessing which options would cause political difficulties for SCC. This was judged by engineers as those options which would cause problems over and above normal complaints covered by public relations costs (e.g. sustained involvement in arbitration, legal disputes, etc.).			
EnvRisk The risk that the option will not deliver the expected benefits for the environment over the 40-year lifetime (e.g. the expected benefits of the recycling processes may not be realised if the material could not be recycled afterwards).	(None)	*Benefits* This objective is concerned with maximising the benefits associated with reconstructing the road.	
Transport The environmental effects of additional transport in Surrey for each option based on number of truck journeys. This deals with the additional dust, noise, pollution and disruption effects experienced due to the movement of materials and wastes within Surrey (i.e. local aspects of nuisance not covered by Lifetrans criterion).	*Local Env* This objective captures the wish to maximise local environmental quality by minimising immediate effects on the environment as experienced by residents surrounding the reconstruction site.		
Noise Noise generated at the road site during reconstruction works, which could cause a nuisance to residents.			
Dust Dust generated by the reconstruction works at the road site, which could cause a nuisance to residents.			
Visua The reduction in visual amenity to residents caused by the reconstruction works at the road site.			
Disruption The increased stress caused to local people (including the disabled) by traffic congestion, travel delays, spreading of disruption to other local areas in Surrey and blocked access for pedestrians at the road site.	*Socio-Econ* This objective describes the desire to maximise social and economic benefits experienced by local people as a result of carrying out the reconstruction works.		
Local Risk The increased risk to local people from the reconstruction site, given that all reasonable safety precautions had been taken.			
GHG Total greenhouse gas emissions expressed as CO_2 equivalents (IPCC, 100 years) for extraction, manufacture, transport and construction over the 40-year period for each option.	*LifeCycleEffect* This objective deals with the wish to maximise environmental quality by reduceing environmental impacts from the road construction processes over the whole road life cycle for 40 years, from extraction of materials to managing waste at the end of life.		
Waste Total waste produced over the life cycle requiring landfill disposal (i.e. non-hazardous waste).			
Haz Waste Total hazardous waste produced over the life cycle requiring special disposal.			
Asphaltenv Sulphur dioxide emissions and visual impact on buildings from asphalt production.			
Energy Extraction, manufacture, transport and construction energy use in reconstruction options over the 40-year period.			
Hum Tox Human population exposed and the extent of exposure to toxic pollution from a life cycle perspective.			
Aquatox Population exposed and the extent of exposure to toxic pollution from a life cycle perspective via water.			
Terrtox Population exposed and the extent of exposure to toxic pollution from a life cycle perspective via soil.			
Lifetrans The environmental effects of additional transport in Surrey based on the number of truck journeys.			
Extract The environmental effects of extraction of materials such as noise, dust, transport and pollution expressed as the product of quantity of material moved and the severity of known effects.			

Table 6: Summary table illustrating the scores[a] and weights for each criterion

Objective	Criterion	Scale	Option Number						Cumulative Weight
			1	2	3	4	5	6	
costs	process	data, £/m^2	35	35	12	12	11	11	*31*
costs	failure	preference	100	80	20	0	25	15	*1*
costs	pub rel	preference	0	15	90	100	90	100	*3*
costs	local accept	preference	0	10	90	100	90	100	*15*
benefits	env risk	preference	100	100	0	0	50	50	*1*
local env	noise	preference	0	0	100	100	100	100	*5*
local env	dust	preference	60	60	100	100	0	0	*2*
local env	visual	preference	0	0	100	100	100	100	*1*
local env	transport	data, truck journeys	221	166	82	76	81	75	*0*
socio-econ	disruption	preference	0	0	100	100	100	100	*15*
socio-econ	local risk	preference	0	0	100	100	100	100	*1*
life cycle effect	GHG	data, CO_2 equivalents (IPCC, 100 years) x 10^2	2186	1463	1479	1406	1456	1383	*2*
life cycle effect	waste	data, tonnes	1131	94	200	105	208	114	*5*
life cycle effect	humtox [b]	data, kg 1,4-dichlorobenzene equivalents	1998	1428	1519	1462	2095	2038	*3*
life cycle effect	asphaltenv	data, kg SO_2 equivalents	71	71	48	48	48	48	*1*
life cycle effect	energy	data, MJ x 10^3	3878	3043	3237	3153	2537	2454	*3*
life cycle effect	haz waste	data, kg	6172	1	852	1	852	1	*5*
life cycle effect	aquatox [b]	data, kg 1,4-dichlorobenzene equivalents	628	496	536	523	386	373	*1*
lifecycleeffect	terrtox [b]	data, kg 1,4-dichlorobenzene equivalents x10^1	3017	2108	2266	2175	3520	3429	*2*
life cycle effect	lifetrans	data, tonne-km x 10^2	3861	3308	1666	1581	1370	1285	*2*
life cycle effect	extract	data, tonnes	1861	981	1148	1060	1192	1104	*3*
Total Preference Score			**4**	**26**	**91**	**94**	**88**	**92**	

[a] This table illustrates the actual data scores obtained for each criterion where these are quantitative, not adjusted into preference scales; e.g. for 'process', the figures are in £/m^2, rather than stated as preference scores. However, the Total Preference Score indicated is an aggregation of preference scores and weightings against each of the criteria, giving the overall ranking preference for each option derived from the model.

[b] Values used obtained using characterisation factors in Guinée et al. 1996.

used to calculate aggregated scores for each option originally were set at 50:50 for costs:benefits. The participants were interested in how the weighting applied to the costs objective affected the overall preferences, especially since some of them considered reducing costs to be the imperative policy objective. The lines on the diagram in Fig. 3 refer to the changes in total preference score for each of the six options as the weighting applied to the cost objective is increased from 0 to 100; the vertical line indicates the original 50:50 weighting. The shaded area indicates the range over which Option 4 dominates, corresponding to weighting from 0 to 75. At weights of 75 or more applied to the cost objective, Option 6 is preferred by a very small margin. However, since the preference for Option 6 is less stable over the range of applied weights (as shown by the steeper gradient of the line in comparison with Option 4), Option 4 would be a better choice overall. The results were similarly robust over the complete set of preferences and options. Clearly, Options 1 and 2 are less preferred than the remaining options over the whole range of weights for costs. Option 2 shows a large variability in scores over the range, being preferred more when the weighting applied to the 'costs' objective is low.

Generally, the main benefit from integrating the salient data from the LCA study with other relevant criteria in the MCDA model was that it allowed the group to understand the relevance of differences in preference between options. For example, the difference of 2 on the preference scale between Options 4 and 6 means little to participants in isolation. It is the process of examining the reasons for differences in preference between the options against criteria and whether this difference matters that engenders understanding of the consequences of choosing a particular option. It is also valuable to understand how to improve the performance of more poorly performing options, should it be necessary to use them. For example, it is sometimes not practical to use in-situ recycling methods (e.g. where there

are many services underneath the road) and may then be necessary to use ex-situ recycling methods (such as Option 2) in these circumstances.

2 Discussion

2.1 Including relevant local and global environmental criteria in local decision processes

Conventional LCIA methodology leads analysts to make assumptions about the type of environmental information that will be useful for decision makers and relevant to their decisions, both prior to and during the analysis. Using MCDA through decision conferencing prevents this by eliciting directly from participants the information they require for the decision at hand. A natural tension exists between the need to standardise information requirements for completeness in assessment and the needs of a particular local decision context, since in the former case the information required for the decision process may not be generated while in the latter there is a possibility that important data may be overlooked. This case study demonstrates that the use of LCA alone would have neglected a whole range of local decision criteria (e.g. noise, visual amenity), while the use of the decision conference alone might have lacked the necessary data and the benefit of a systems approach to evaluating environmental impacts from a more regional or global perspective. However, it also demonstrates that a combination of both approaches may ensure that awareness is raised about global environmental concerns not normally included in local decision making, whilst also including local environmental issues as a legitimate concern[15].

2.2 Evaluating options against environmental criteria

The primary objective of using LCA within the MCDA framework was to provide information to allow quantification of preferences for each option against environmental criteria. To be in a compatible format for the MCDA methodology, the LCIA results should describe the consequences of the environmental interventions for each option, so that the stakeholders can relate this information to their decision criteria. Without this perspective, it is not possible for stakeholders to articulate preferences in an informed way within the MCDA framework. In the case study, some incompatibilities were observed between the data available from the problem-oriented LCIA and information required by participants to evaluate the options. The most explicit example was human toxicity. The 'humtox' criterion elicited in the decision conference was defined as the 'human population exposed, amount and type of exposure to toxicity from the extraction and transport of materials for road maintenance via air water and soil'. However, the output of the problem-oriented LCIA, regardless of toxicity model used, gives no direct indication of the number and type of local people exposed to pollutants, how much of the pollutant they are exposed to and the likely consequences of exposure. In fact, this implies that the location of releases would need to be known in order to estimate the number and type of people exposed, but LCA provides no means to assess the presence of 'target receptors'; this is more the province of tools used in EIA procedures (Wrisberg et al. 2002). This implies that there is a need to resolve the degree of spatial specificity in environmental data required to address local as well as more generic policy decision processes, due to the potential to invoke different definitions of relevant decision criteria.

In decision making at a global or a regional level, the omission of this level of detail may be justified because describing potential effects independent of location is usually sufficient to assess the likely consequences. However, at the local level, the consequences of a release of a pollutant may be valued differently by decision makers and key players if it occurs, say, next to a school rather than in the middle of an area of outstanding natural beauty or in an industrial area. These nuances in consequences are an important part of the MCDA model, as they explain why the participants are concerned about the environmental criteria and hence the strength of preference expressed for each option. The process must capture these distinctions if the results are to be sensitive enough to relate directly to the concerns of decision makers. Achieving this level of sensitivity in scores and weights for human toxicity in this case study would have required an approach to impact assessment that accounted for the presence or absence of target receptors and the existence of a pathway for exposure of the target receptor to the pollutant (i.e. essentially a risk assessment approach).

'Midpoints' approaches to LCIA combine the quantification of environmental interventions with accounting for the fate of the substances in the environment, usually by modelling. This study, using the problem-oriented approach to toxicity modelling, has demonstrated that this approach could not provide the requisite data. By contrast, 'endpoints' approaches should describe the consequences of the environmental interventions (Guinée et al. 2002, pp. 529–538). However, these approaches tend to aggregate impacts and contain implicit weighting methods and thus were also unsuitable for this case study; it cannot be assumed that generalised endpoints will necessarily provide surrogates for the locally generated criteria arising directly from the participants' concerns. The definitions of such locally generated environmental decision criteria (and hence the scores and weights accorded to them) in MCDA are specific to the decision at hand, whereas LCIA results with implicit weightings do not address the specific decision criteria and their associated measurable attributes. We agree with the observation that using 'expressed preference methods' such as decision conferencing will have serious implications for the use of 'generic weighting sets' in LCIA and that this is an important area of research to be developed (Udo de Haes et al. 2002, pp. 202–203).

2.3 Double counting in environmental criteria

Some environmental interventions were double counted in the impact categories used in the case study, and therefore

[15] Raising awareness of the benefits of using life cycle approaches to evaluate the environmental impacts of products and services is often voiced as a key objective for LCA (see for example Allen et al. 1997, Cowell et al. 1997, Rebitzer et al. 2004, Sonnemann 2004). In view of this, it follows that engendering understanding of the way in which these impacts relate to local decisions should be a priority, in addition to efforts to educate participants about how to use the approaches in practice.

appear to have an unjustifiably inflated significance in the decision. For example, emissions of cadmium in LCIA contribute towards increased human exposure and increased exposure of the environment to toxicity (midpoints), and thus appear in three different decision criteria in the MCDA model: 'humtox', 'aquatox' and 'terrtox'. Without the additional risk assessment information discussed in Section 3.2, it is not possible to make judgements about the probable consequences of the release at local level. Mutual preference independence of criteria is a fundamental requirement to allow the use of the simpler MCDA models, unless the non-independence is otherwise accounted for by using more complex modelling techniques or the decision criteria are separated sufficiently so that they can be considered independent. Failure to achieve this causes certain attributes to have a much larger influence in the decision than they should from a rational perspective[16]. Using LCA within a MCDA framework is thus likely to lead to changes in the definition of impact categories and/or calculation methods for established LCIA methods, either to prevent double counting or to account for non-independence with additional modelling.

2.4 Relative and absolute analysis of impacts

The case study has illustrated that different levels of data quality may be required for a comparison of environmental impacts for decision options, rather than an absolute analysis of their magnitude[17]. The former implies that qualitative information may be sufficient to compare impacts, whilst the latter would require a detailed and quantitative analysis. The former could also be used as a legitimate means to simplify data collection for the LCI. There is also the possibility of identifying early any criteria that would require the collection of very detailed analytical data[18]. Holding a decision conference as part of the scoping process prior to collecting any LCA data would allow collation of the environmental decision criteria relevant to the decision at hand and appraisal of whether data should be qualitative and/or quantitative. It would also allow early dialogue between stakeholders to decide how to include or exclude environmental interventions in the LCI as they relate to locally generated decision criteria.

Given that one of the practical criticisms of LCA has been the time and expense involved, it may be worth investigating further whether these potential benefits can be realised. Ensuring that data collection is focussed on information with direct relevance to the decision at hand may reduce the overall time taken to carry out the study. Of course, this may mean that the results obtained would only have relevance within the specific decision context where they were developed and would not be generally applicable, but it ensures that the results can be used and understood by the participants in the decision. This certainly does not preclude the use of full LCA studies to calculate the absolute magnitude of environmental impacts, but it is postulated here that supporting local decision processes may require a different approach and that this merits further investigation.

2.5 Identifying trade-offs between objectives and promoting agreement on preferred options

The case study has clearly illustrated that the inclusion of diverse criteria is important in local decision processes, to assist groups of stakeholders to make more sustainable choices. It was easier for participants to differentiate between options using the LCIA results within the MCDA framework, rather than using LCIA alone[19]. The creation of the MCDA model and its exploration during the decision conference clearly revealed the distinctions between options and the trade-offs involved in choosing between them, providing the basis for discussion between participants. The sensitivity analyses allowed agreement to be reached on a choice of option, without agreement on the scores or weights for certain criteria[20]. This supports the findings in the literature that MCDA is capable of supporting group decision-making without the need for prior consensus (Keeney and Raiffa 1993, p. 541) and that sensitivity analysis may assist in resolving disagreements between interest groups by focussing on areas of agreement as well as the value conflicts that are usually the subject of debate (DETR 2000, p. 67).

3 Concluding Remarks and Recommendations for Further Work

Methodology to support local sustainable development decisions must include a means to assess the consequences of choices against all relevant criteria; economic and social, as well as environmental. The successful use of LCA within a MCDA framework through the process of decision conferencing demonstrates a possible means of developing a methodology to carry out such assessments. The success in supporting group decisions, including assisting with eliciting value judgements and mitigating conflicts, demonstrates the value of this approach and that it merits further investigation. However, some difficulties have been encountered in using LCIA in an MCDA framework, which suggests that LCIA requires adaptation to support local decision-making; a fundamentally different, 'case by case' approach to im-

[16] In LCA, this problem has been anticipated by previous authors who regard impact assessment in LCA as structurally similar to decision analysis (for example, see Hertwich and Hammitt 2001; Seppälä et al. 2002).

[17] Here, comparison (or relative analysis) means evaluating the magnitude of environmental impacts for each decision option considered within the scope of the decision at hand. Absolute analysis of environmental impacts implies that the actual magnitude of those impacts can have relevance outside the immediate decision process.

[18] For example, the 'Noise' criterion was defined by the group as "the noise generated at the road site during reconstruction works that caused a nuisance to residents". Assuming that the noise generated by the in-situ process and the conventional reconstruction process are equivalent (which was valid in the opinion of all the highway engineers in the group), it follows that the main variable in the potential to generate noise is the length of time for which the works are carried out. Since conventional reconstruction takes approximately four times longer than in-situ recycling, conventional reconstruction can be considered to produce four times as much noise nuisance as linear quarrying. There is no need to collect noise data to evaluate this parameter: a qualitative comparison is sufficient to conclude how the options should be evaluated.

[19] For example, this is demonstrated by the ability of the former to illustrate that Option 2 was clearly much less preferred than the in-situ recycling options, despite having LCIA results of similar magnitude (see Section 2.4).

[20] An example here is the analysis of the weighting applied to the 'costs' objective in the model, which caused some consternation among the participants. Over most of the range, Option 4 was preferred, showing the relative insensitivity of the model to such variations (see Fig. 3). This allowed agreement to be reached on ranking without agreement on the weight accorded to the objective.

pact assessment may be needed to ensure its relevance to the decision context. This has been shown to be particularly significant for the toxicity results, where the wide variation between different methodologies inevitably reduces the confidence in the results. It is recommended that further investigation should address the following objectives:

- Directly addressing environmental decision criteria generated within the context of local decisions;
- Refining the assessments of toxicity to make them more usable in this type of decision process;
- Assisting decision makers and key players to evaluate the consequences associated with the choice of options against environmental criteria in local decision processes;
- Preventing double counting of environmental criteria;
- Investigating whether there is any potential to streamline data collection;
- Confirming the potential to assist with conflict resolution between interest groups.

As Hertwich and Hammitt (2001) have observed, "there exists no unique best indicator for environmental harm, because evaluations of environmental detriment can be based on different, legitimate sets of values and on competing, justifiable notions of rationality". This case study has demonstrated how different value sets can be recognised in a decision using LCA data alongside other information. Although this case study only involved internal SCC personnel in the decision process, this methodology also lends itself to closer working with external stakeholders due to the potential for conflict resolution and consensus building via the explicit discussion of values. This is an area of research deserving attention in the future, to confirm that the methodology is capable of supporting strategic decision processes, particularly where diverse groups of stakeholders are involved in choices of more sustainable products or services.

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